# Induction Acceleration of a Proton Bunch in the KEK 12GeV PS

**March 18th, 2005**
***BNL***


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**with many thanks for contributions from**

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**A.Tokuchi and A.Kawasaki,** ***Nichicon (Kusatsu)***
**J.Kishiro, M.Watanabe, and M.Shiho,** ***JAERI***
**K.Horioka and M.Nakajima,** ***Tokyo Institute of Technology (TIT)***
**M.Sakuda,** ***Okayama University***

# Outline of my talk

**(1) Brief review**

**What is *Induction Acceleration (Principle)*?**
**Early history at KEK on induction devices R&D and applications**
**What is *Induction Synchrotron (Concept)*?**
**How is a *Super-bunch* generated there?**

**(2) Outline of the POP experiment for *Induction Synchrotron* at KEK**

**(3) Technical Aspects of Induction Accelerating System**

**(4) *Induction Acceleration* experiment**

**(5) *Trapping* in induction step-barriers**

**(6) *Focusing-free Transition Crossing* (FFTC)**

**(7) Summary**

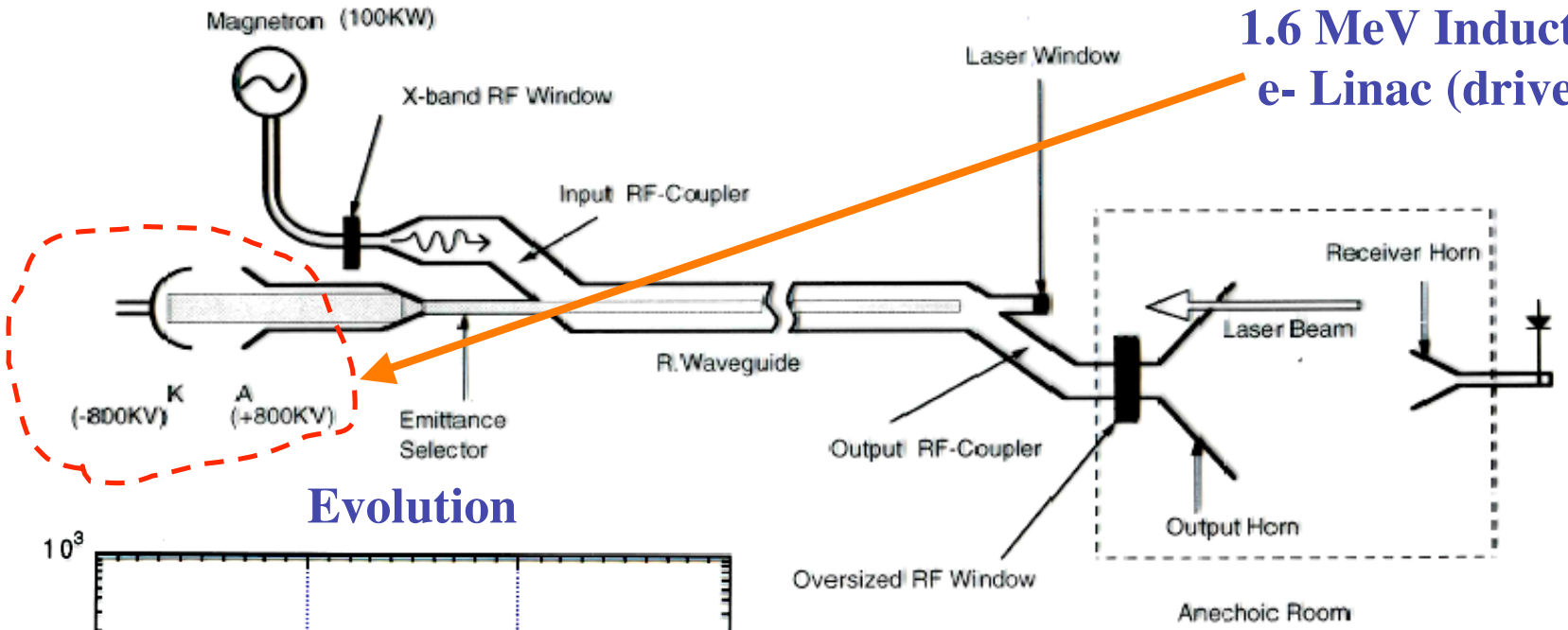
# Brief History of Induction Accelerators

| | Linac | Circular Machine |
|---|---|---|
| 1940 | | Betatron (D.Kerst, 1940) |
| 1950 | *topological modification* → Linear Induction Accelerator (USSR, Christofilos 1959) | |
| 1960 | Astron (Christofilos/LLNL 1968) | |
| 1970 | Electron Ring Accelerator (LBL, USSR) | |
| 1980 | ATA(50MeV, 10kA), ETA(7MeV, 2kA) (LLNL)<br>Ion-channel guided FEL driver (KEK)<br>Microwave FEL driver (CESTA) | Modified Betatron (NRL, Univ. of California Irvine)<br>Induction Racetrack Accelerator (S.Putnam 1987) |
| 1990 | RK/TBA driver (LBL)<br>Heavy Ion Beam Inertial Fusion Driver (LBL/LLNL) | Re-circulator (LLNL terminated)<br>Induction Synchrotron (KEK 1999) |
| 2000 | DART driver (LLNL/LANL) → continue | Super-bunch Hadron Collider (KEK 2002)<br>Acceleration of a proton bunch in the KEK 12GeV PS (2004) |

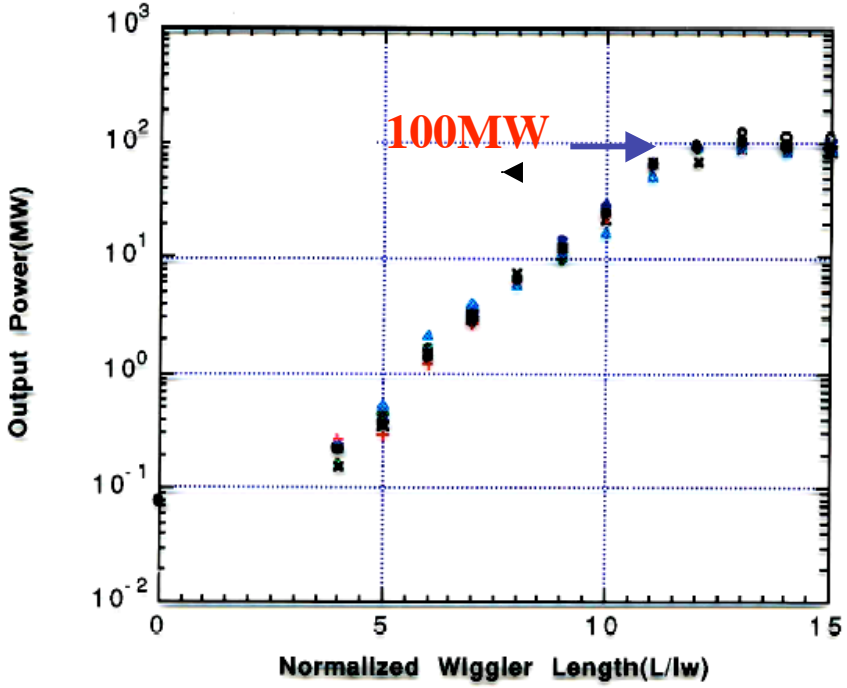
Experimental demonstration/Idea/not completed

(Circular version of Linac)

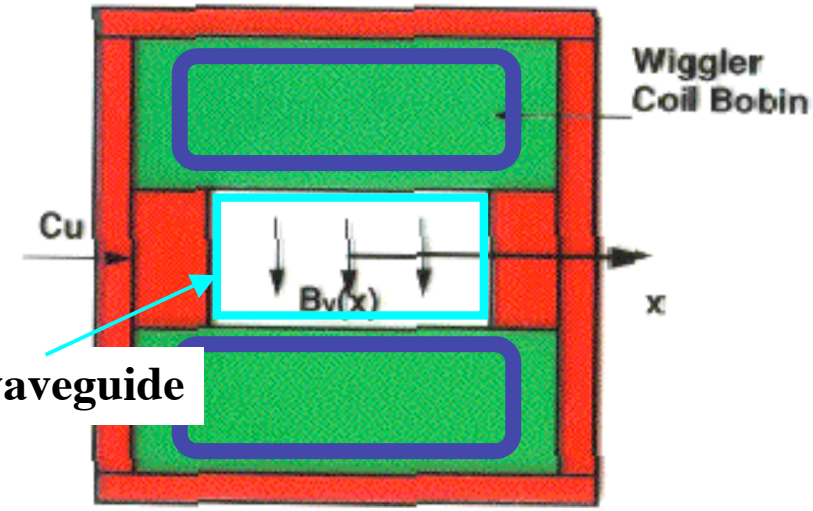
# KEK Ion-Channel Guided Microwave FEL(1987-1994)




## Evolution




## Eddy Current Assist Air-core Wiggler

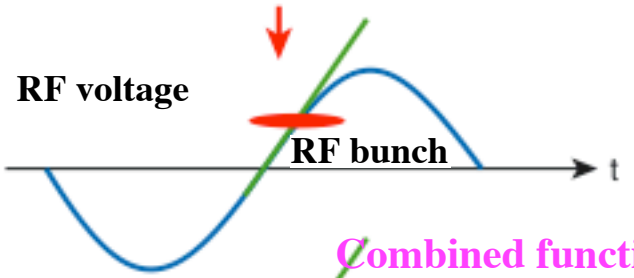


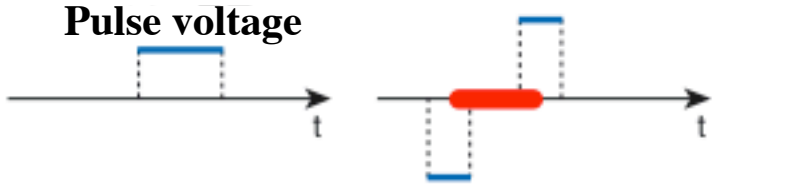
# Concept of Induction Synchrotron

K.Takayama and J.Kishiro, "Induction Synchrotron", *Nucl. Inst. Meth.* A451, 304(2000).

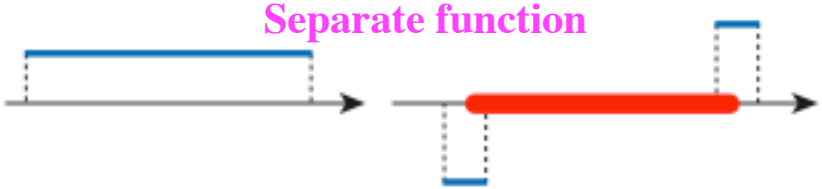
## Principle

### RF Synchrotron



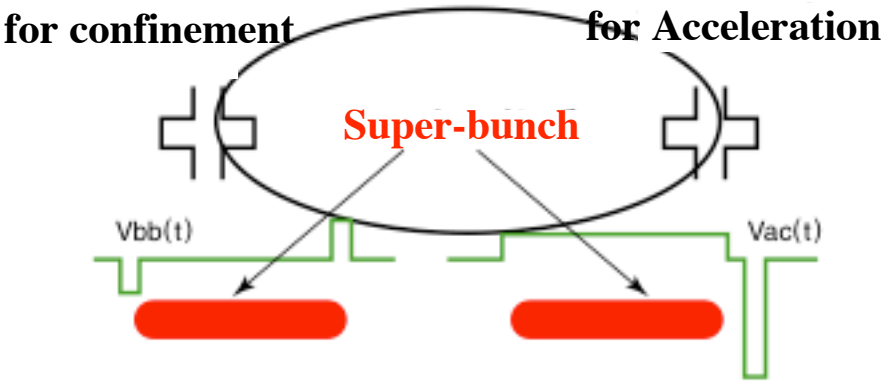

Separate function



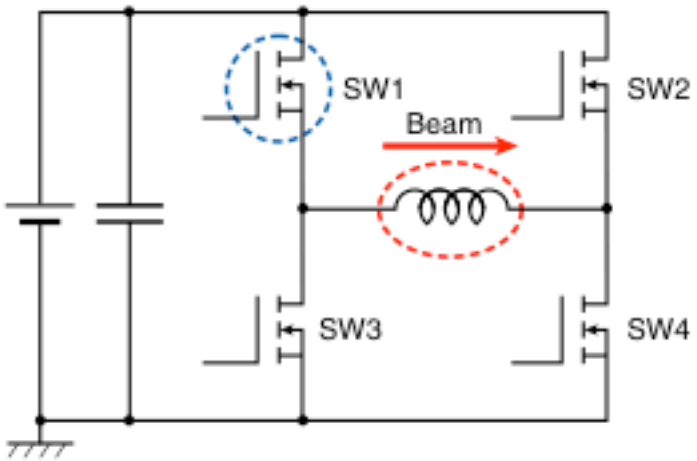
introducing a big freedom of beam handling

Induction Synchrotron

## Image of Accelerator

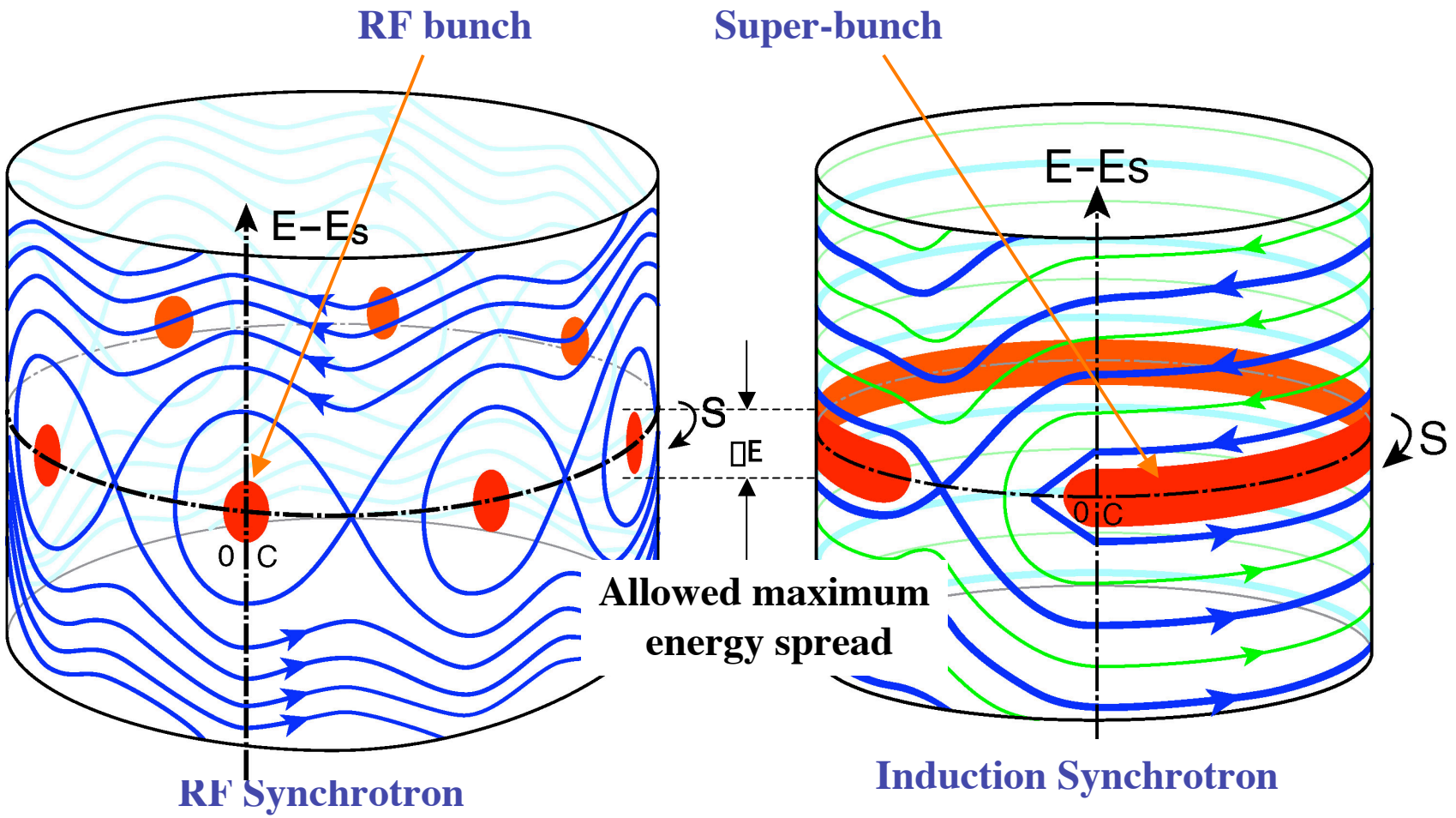



## Modulator Circuit




MHz operation -> serious heat-deposit

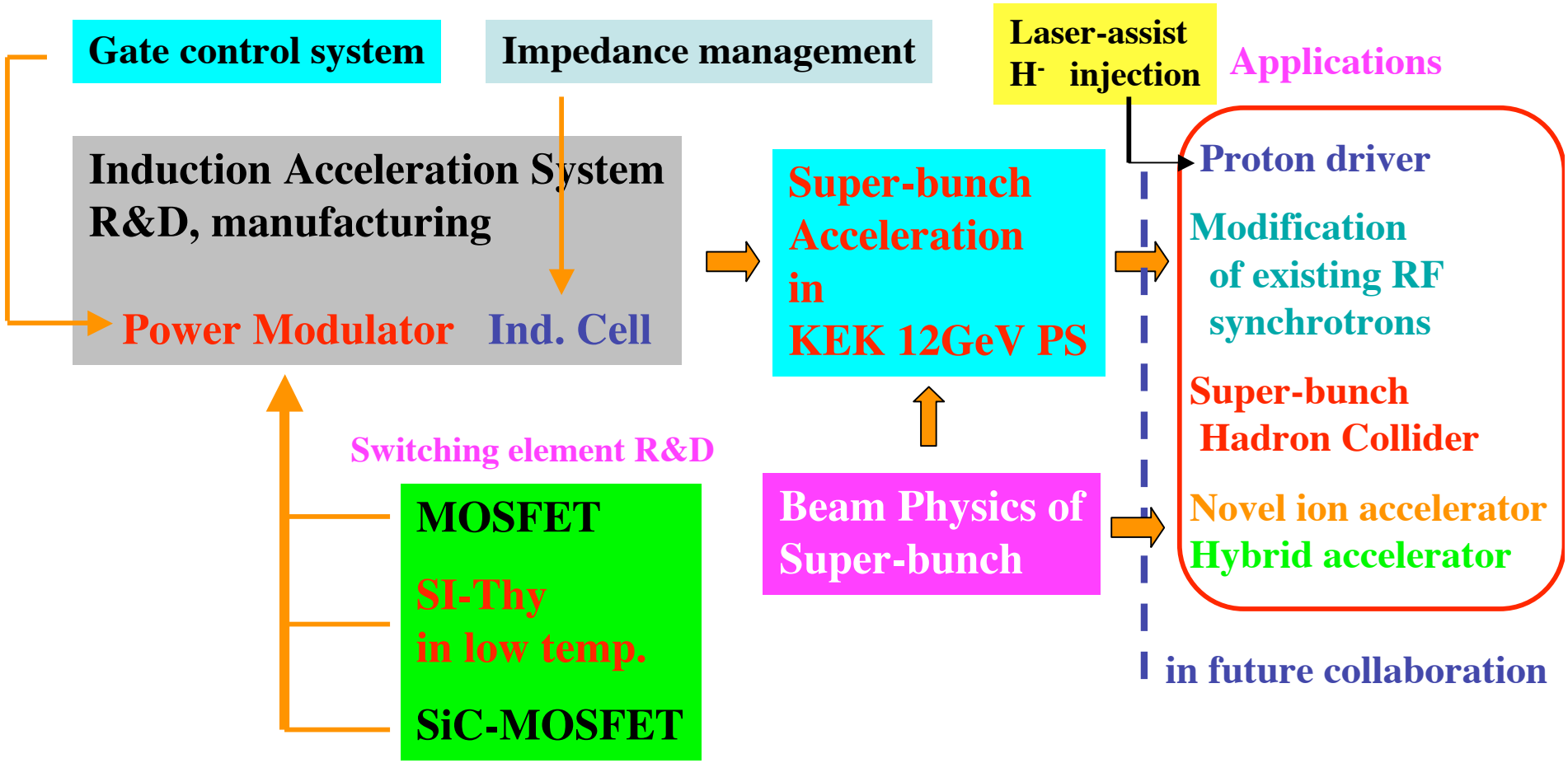
# Difference between RF Synchrotron and Induction Synchrotron seen in Phase-space



# Exploratory Research Project (2003-2007)

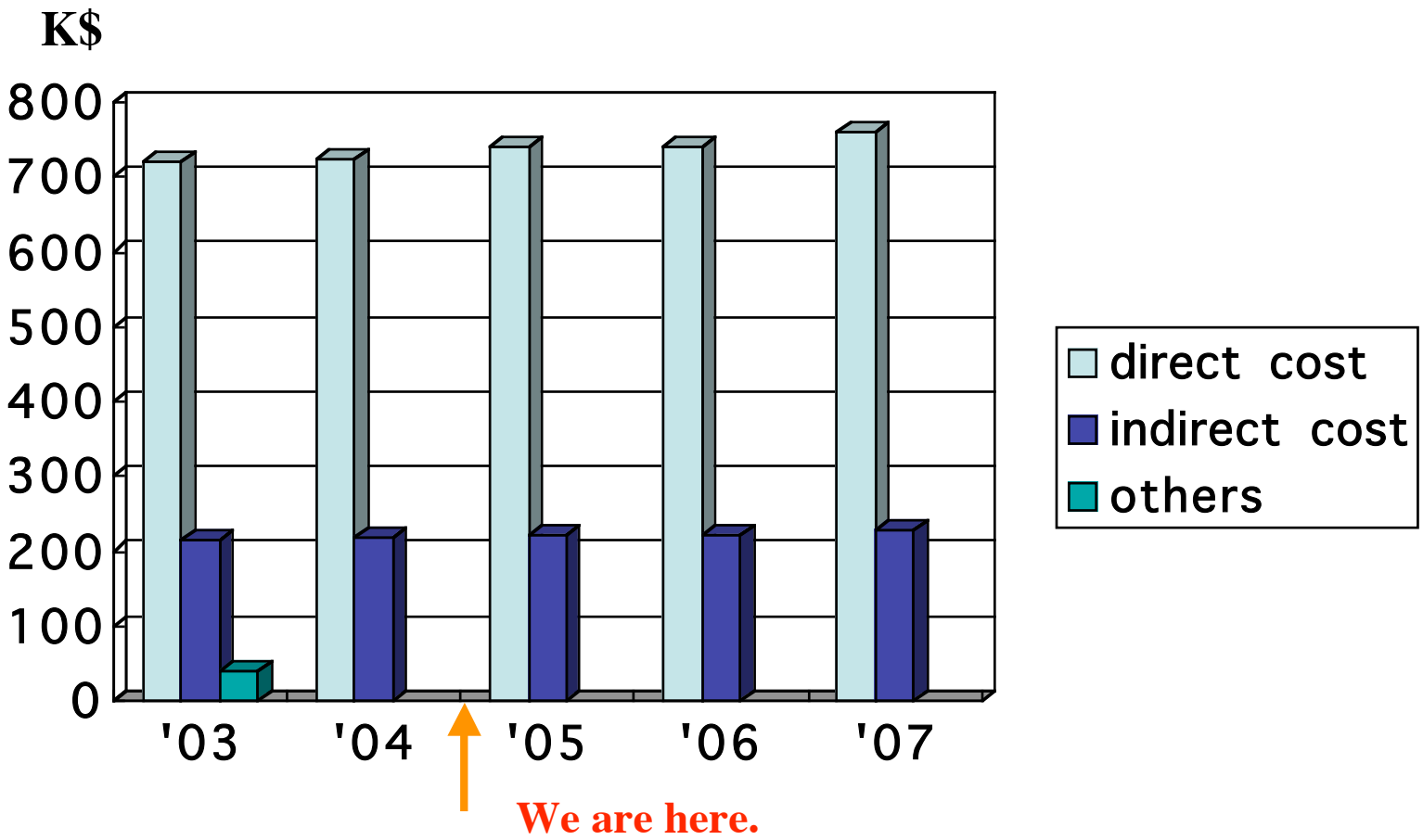
## Super-bunch Acceleration

## Experimental Demonstration of Induction Synchrotron



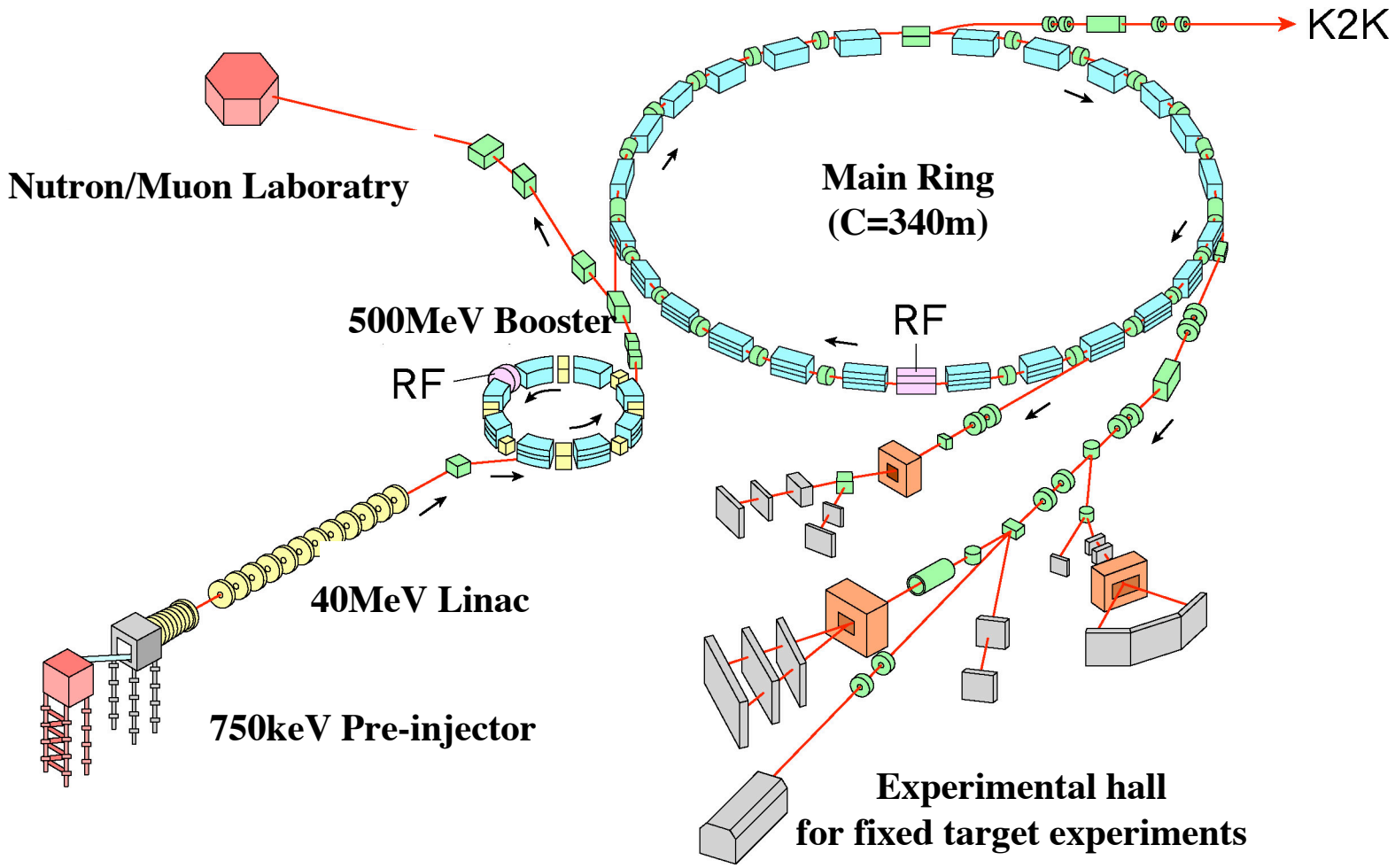

in collaboration with TIT, Nagaoka S&T Univ. and Nichicon

# Funding Outline (fixed)



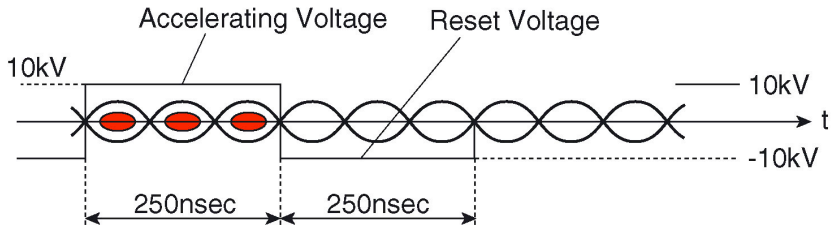

**Including Postdoc/technician's salary but does not include salary of staffs**

# KEK 12GeV PS

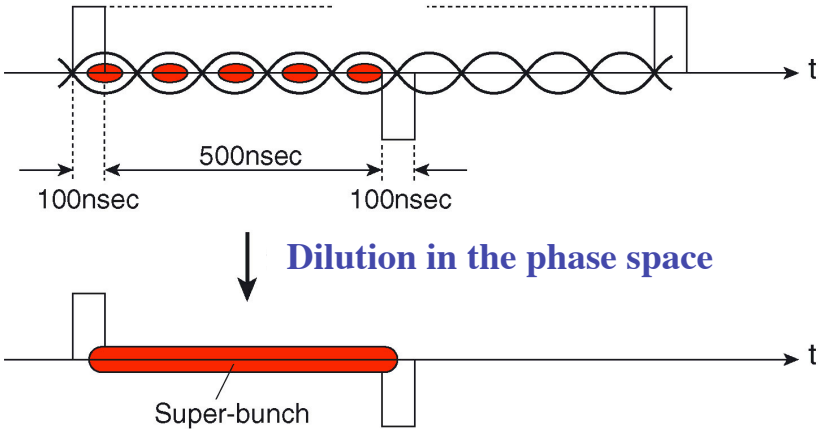

K2K
Nutron/Muon Laboratry
Main Ring
(C=340m)
500MeV Booster
RF
RF
40MeV Linac
750keV Pre-injector
Experimental hall
for fixed target experiments

# Scenario of POP Experiment

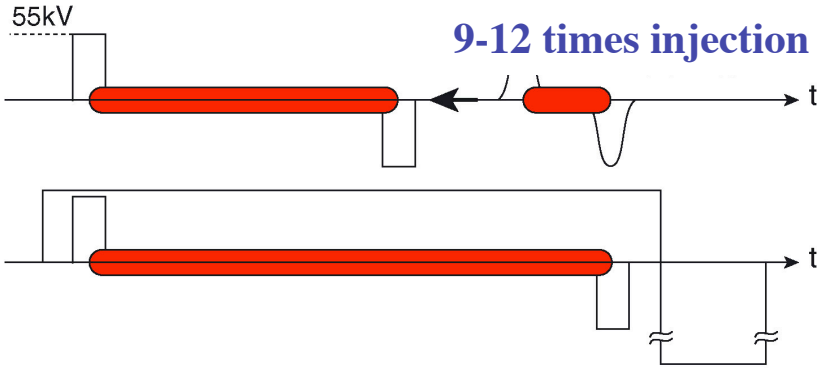
**Step 1** **Acceleration: Induction (500MeV->8GeV)**
**Confinement: RF**




**Step 2** **Super-bunch formation at 500MeV**




**Step 3** **Super-bunch Stacking**
**Acceleration (500MeV -> 8GeV)**



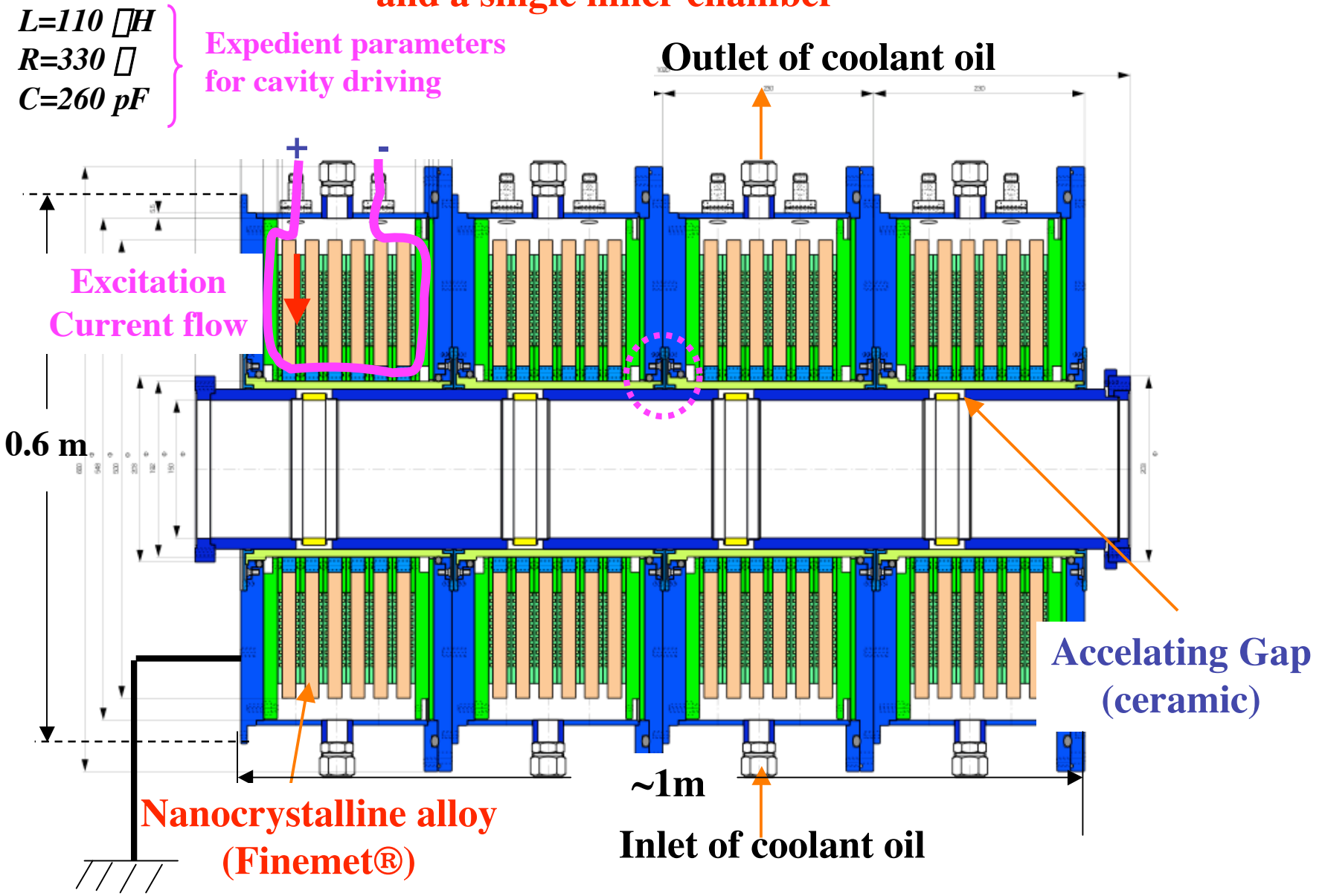

**Final goal is to modify the KEK PS (RF synchrotron) to an Induction Synchrotron at the last stage of its 30 years life.**

# Induction Acceleration Cavity consisted of 4 Cells(2kV/cell)

## and a single inner chamber

*L=110 □H*
*R=330 □*
*C=260 pF*

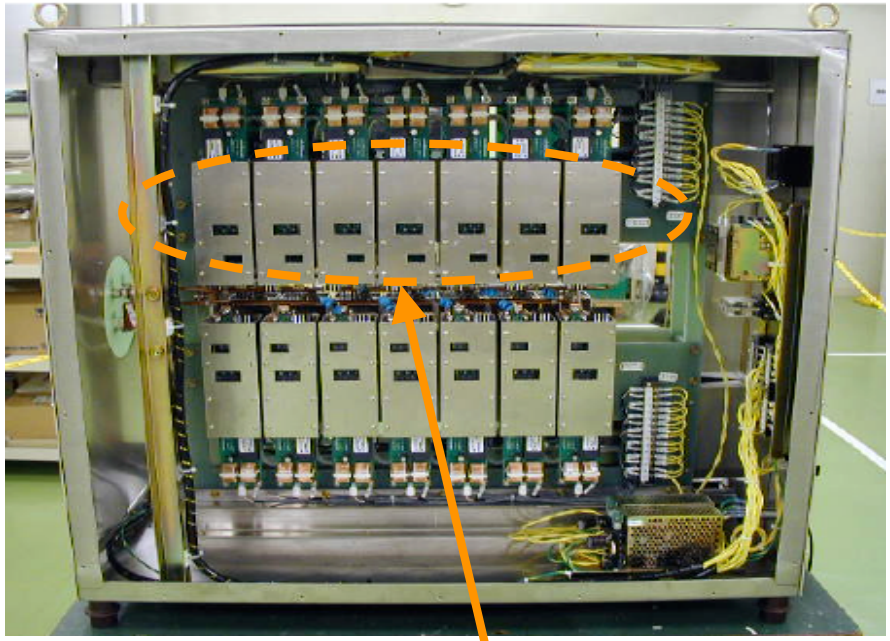
Expedient parameters
for cavity driving

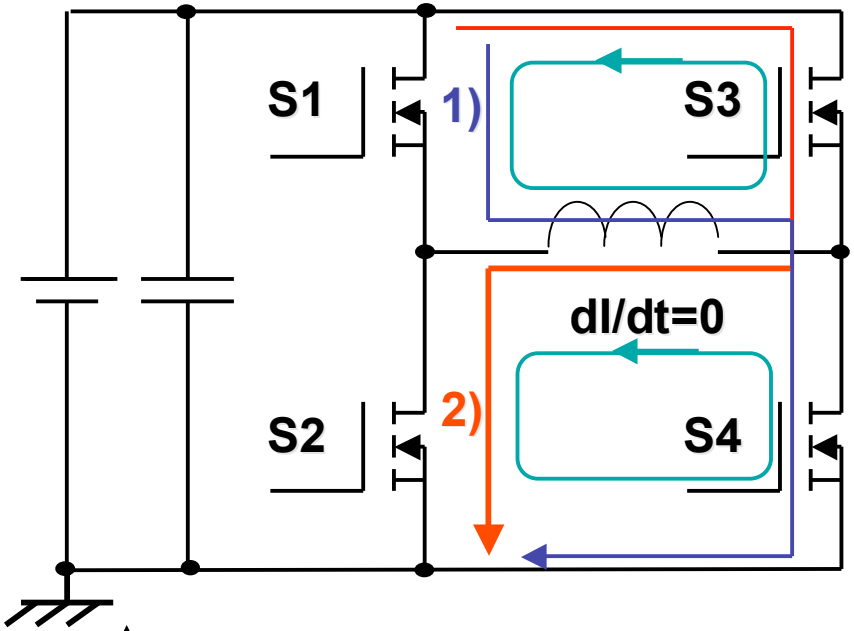



designed, assembled, measured, and installed by K.Torikai

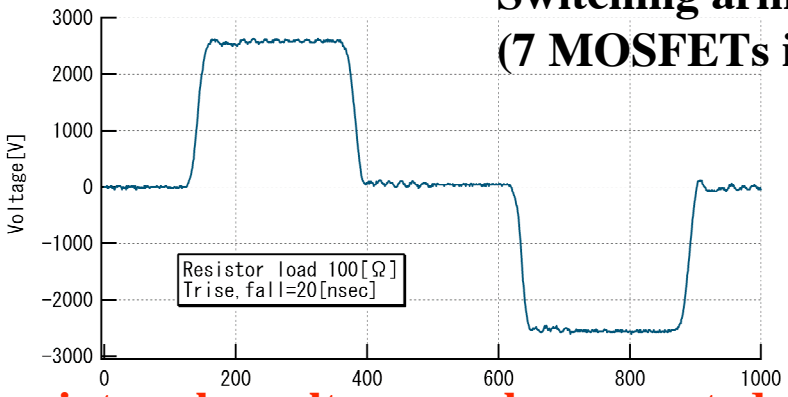
# Pulse Modulator (switching driver):switching sequence, output pulse

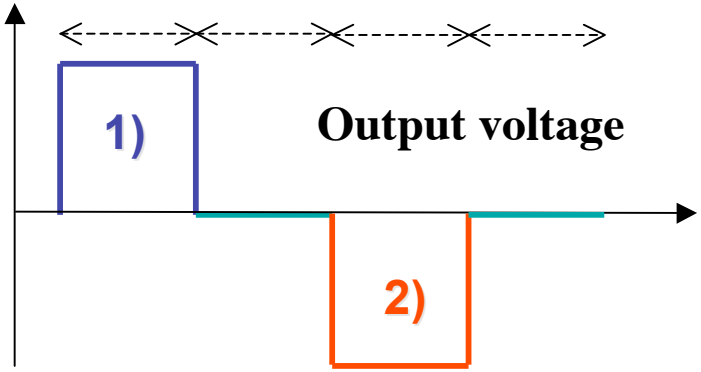
designed and measured by Koseki *et al.*(KEK)
assembled at Nichicon





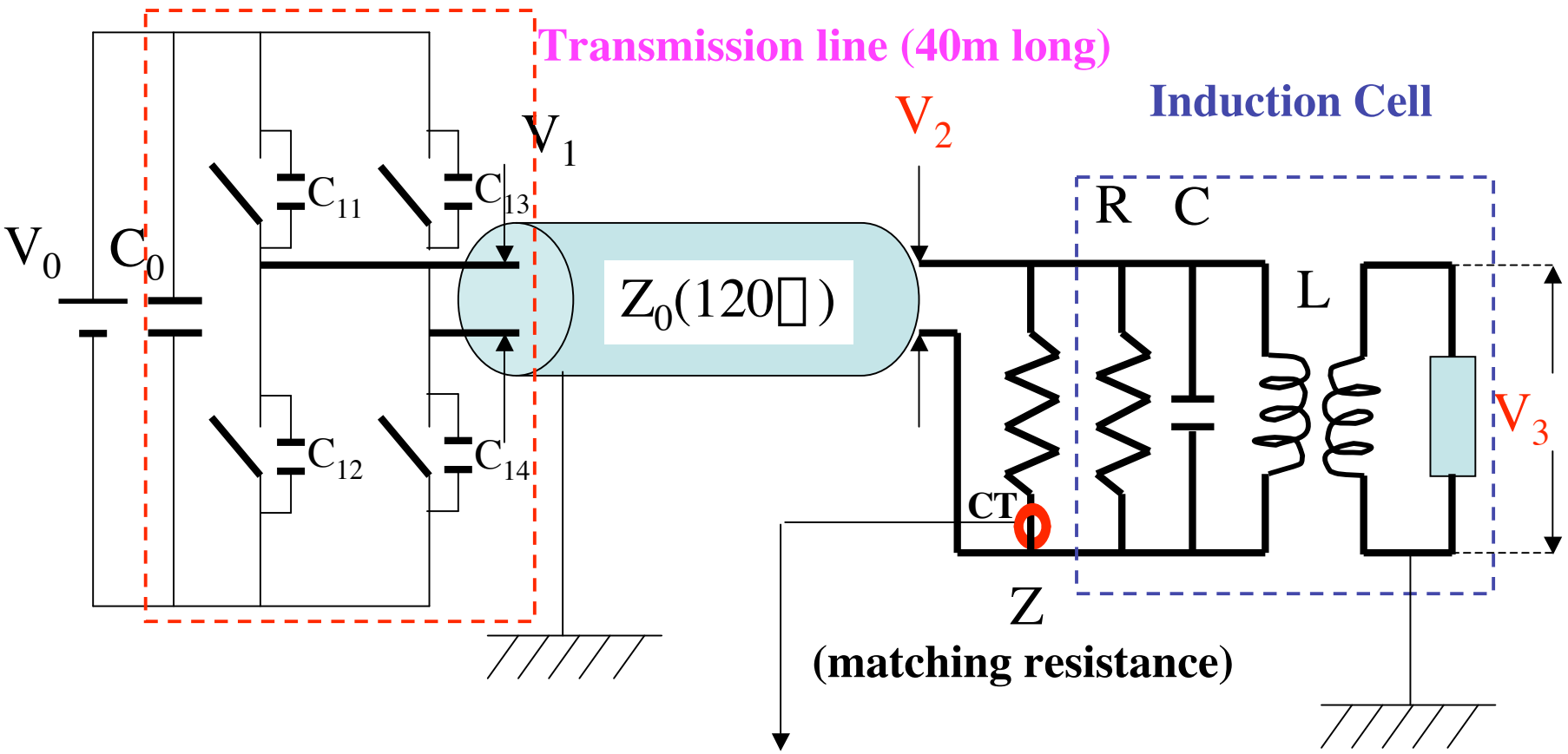

Switching arm S1
(7 MOSFETs in series)




**Key point: pulse voltage can be generated at timing and with pulse duration that you want, by controlling a gate pulse of the MOSFETs.**

# Equivalent Circuit for Induction Accelerating Unit

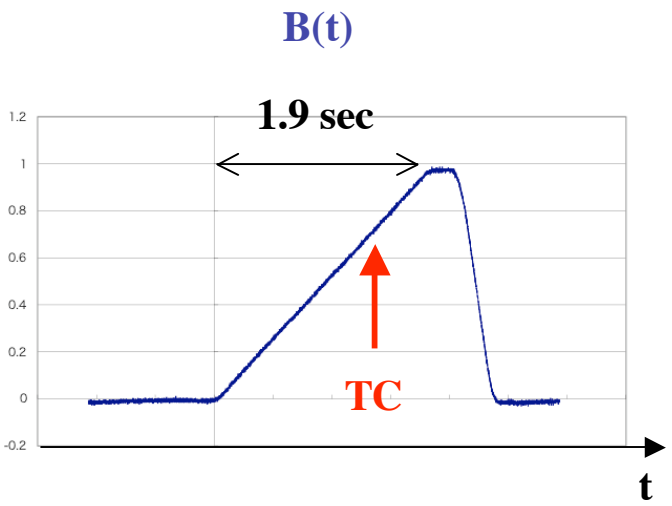


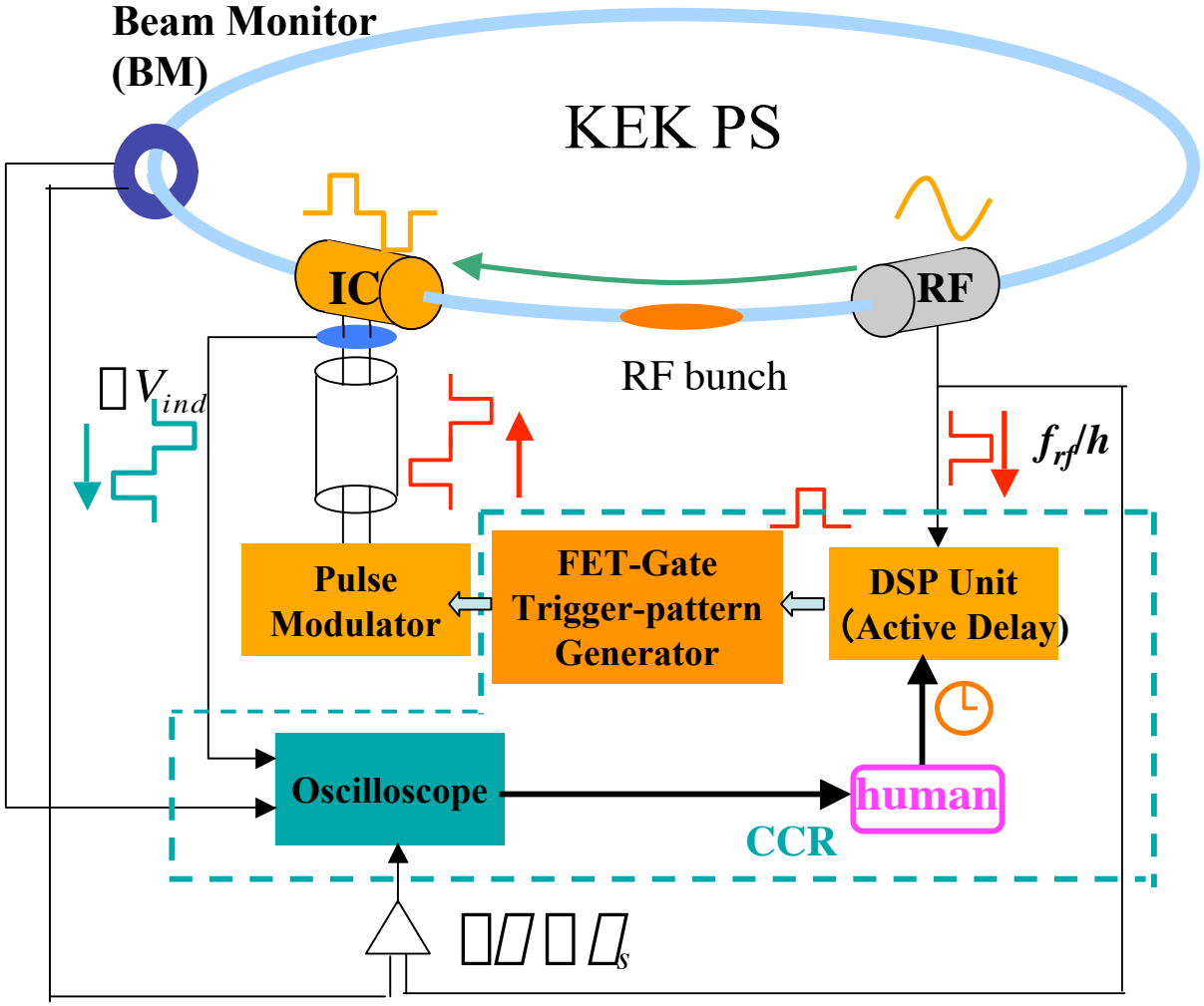

$V_0 \sim V_2 = V_3 \sim ZI_Z$ (calibrated)

$I_Z$ (always monitored at CCR)

# Machine Parameters and Control/Monitoring System

| | |
|---|---|
| Circumference | 339m |
| Trans. energy □ | 6.68 |
| Inj./ext. energy | 500MeV/8GeV |
| Rev. frequency | 667-880 kHz |
| Ramping time | 1.9sec |
| RF voltage | 48 kV |
| Harmonic numb. | 9 |
| Induction voltage | 4.8 kV |



# Progress in Experiments

**2004**

**1st** ***10/3 - 4*** **First demonstration, acceleration from 500 MeV up to 1-2 GeV**

**2nd** ***10/12 - 13*** **Result was unclear, acceleration from 500 MeV up to 6 GeV (just below transition)**

***10/11 -15*** **ICFA workshop HB2004**

**3rd** ***10/17 - 18*** **acceleration from 500 MeV to TC**

**4th** ***10/31 - 11/1*** **acceleration from 500 MeV to 8GeV**

***11/8 - 11*** **CARE HHH-2004**

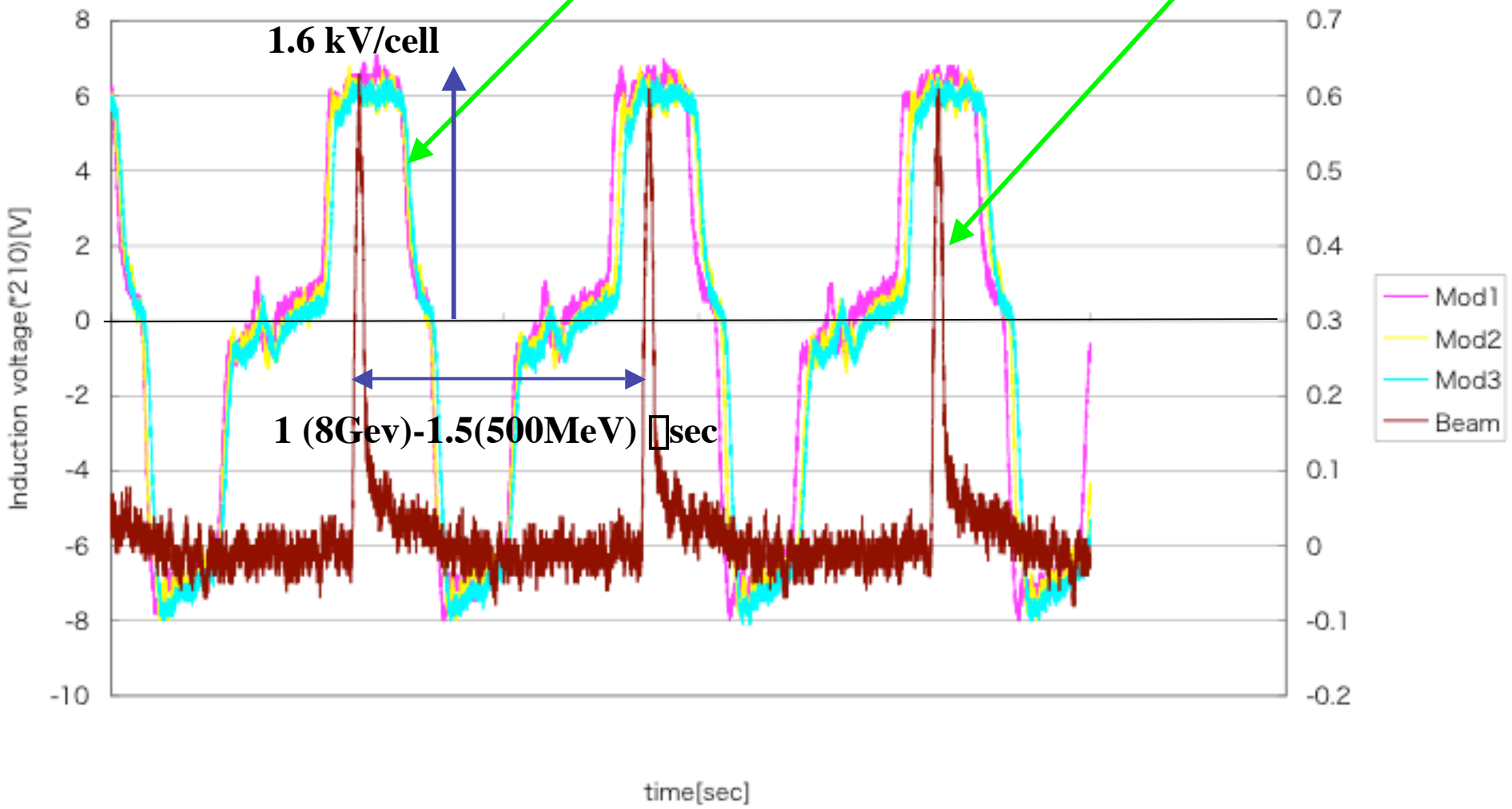
**Nov.-Dec. Induction acceleration in the transient region, such as parabolic ramping of B**

**2005**

**Feb.** **Trapping by induction step-voltages at 500MeV, 600nsec-long bunch**

**March-** **Experimental demonstration of focusing-free transition crossing (just begun)**

# Monitored signals of induction voltage and an RF bunch signal




- Beam bunch signal was monitored at the 4th acceleration gap.
- Coincidence (synchronization) between two signals has been confirmed through an entire acceleration.

# Theoretical background to confirm induction acceleration

**Force balance in the radial direction:**

$$m\gamma \cdot \frac{(c\beta)^2}{\rho} = ec\beta \cdot B(t)$$

**Acceleration equation:**

$$mc^2 \cdot \gamma = \frac{ec\beta}{C_0} \cdot V_{acc}(t)$$

**given by ramping pattern of bending field**

$$V_{acc}(t) = \beta \cdot C_0 \cdot dB/dt$$

**Desired acceleration condition**

**Voltage received by bunch center:**

$$V(t) = V_{rf} \sin\phi_s + V_{ind}$$

$$V(t) = V_{acc}(t)$$

$V_{acc}(t) = V_0$ (constant for linear ramp: $dB/dt$ = constant)

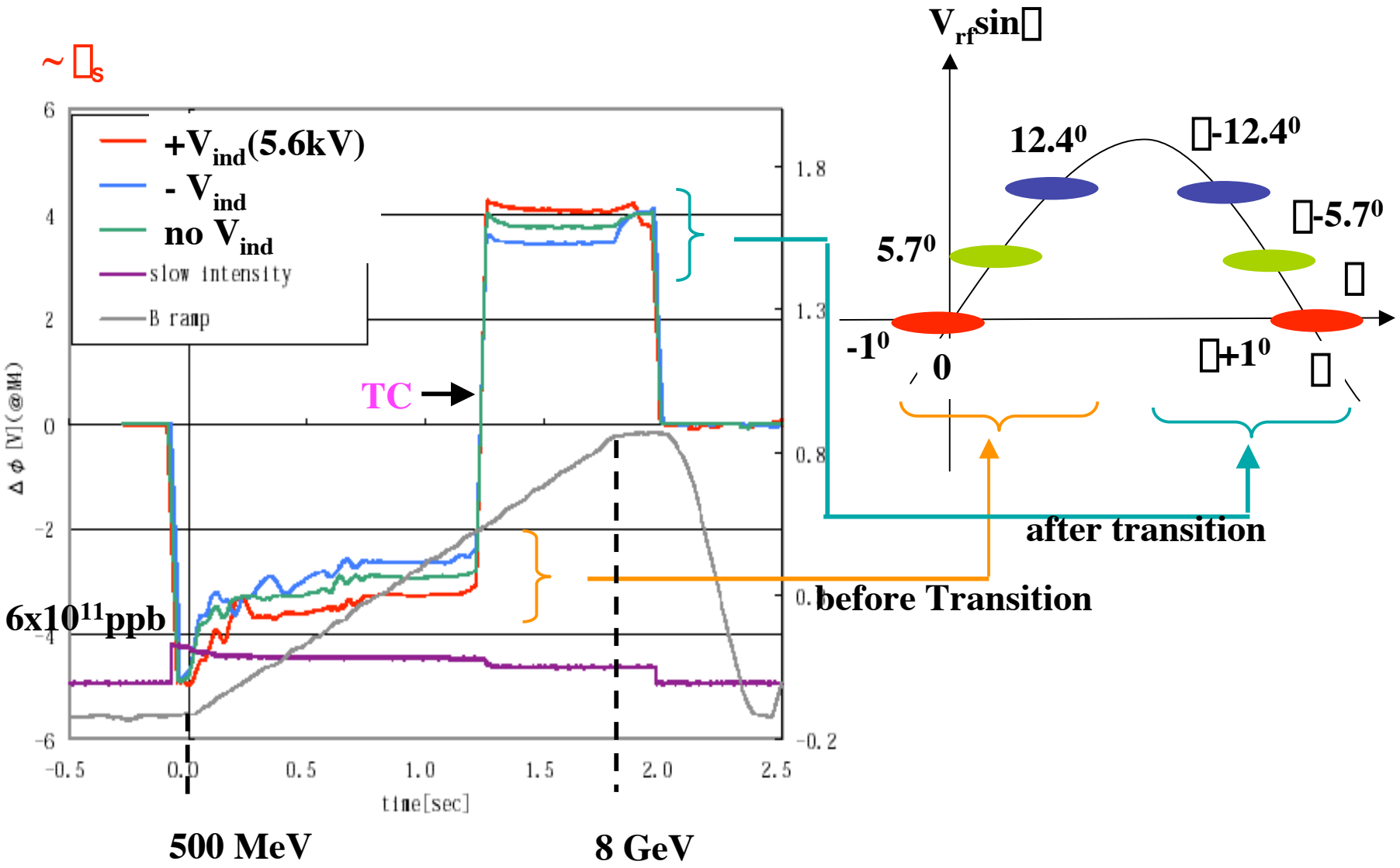
a) $V_{ind} = V_0$ (acceleration) $\quad \phi_s = 0$

b) $V_{ind} = 0$ $\quad \phi_s = \sin^{-1}\left(\frac{V_0}{V_{rf}}\right) = \frac{V_0}{V_{rf}}$

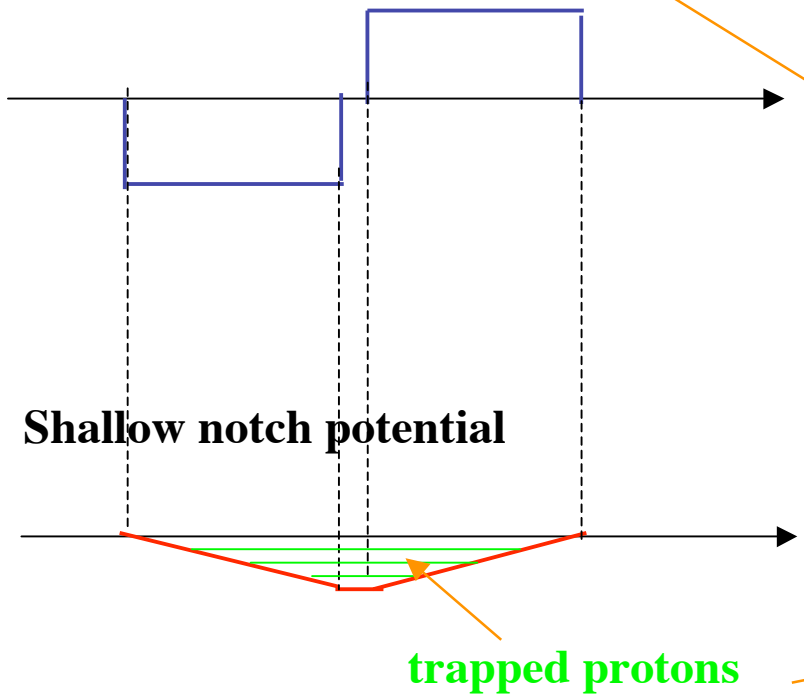
c) $V_{ind} = -V_0$ (deceleration) $\quad \phi_s = \sin^{-1}\left(\frac{2V_0}{V_{rf}}\right) = \frac{2V_0}{V_{rf}}$

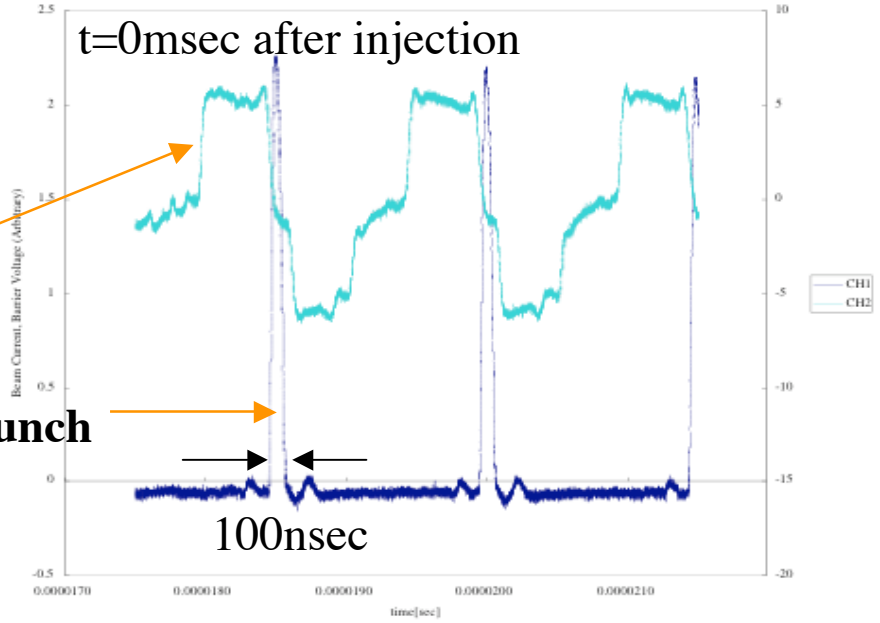
**observable as a relative position of an RF bunch to RF phase**

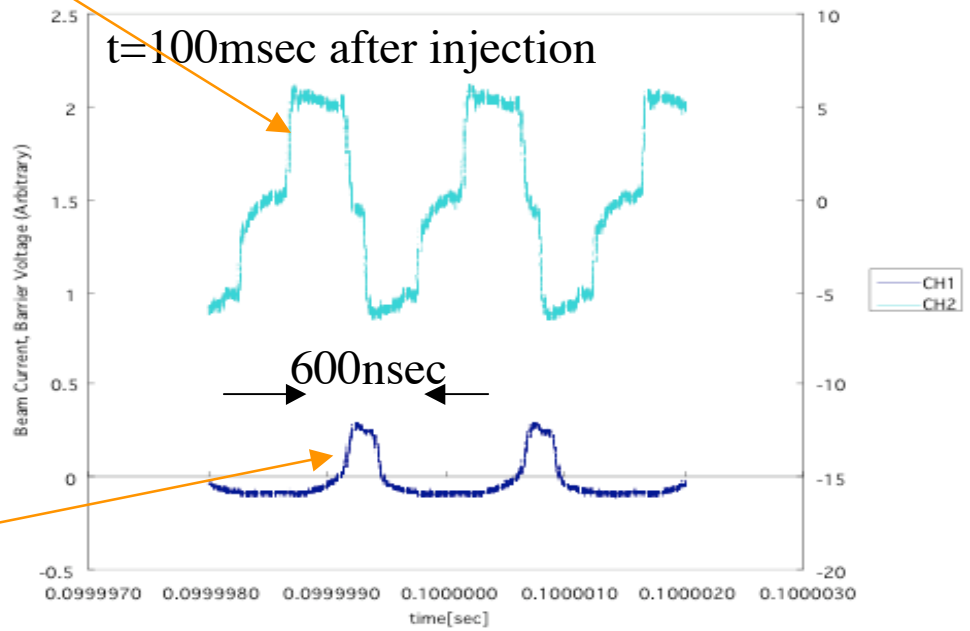
# Experimental Facts: Change in $\phi_s$, Beam Intensity, and B



# Confinement by Induction Step-barriers
## Formation of a 600nsec-long bunch

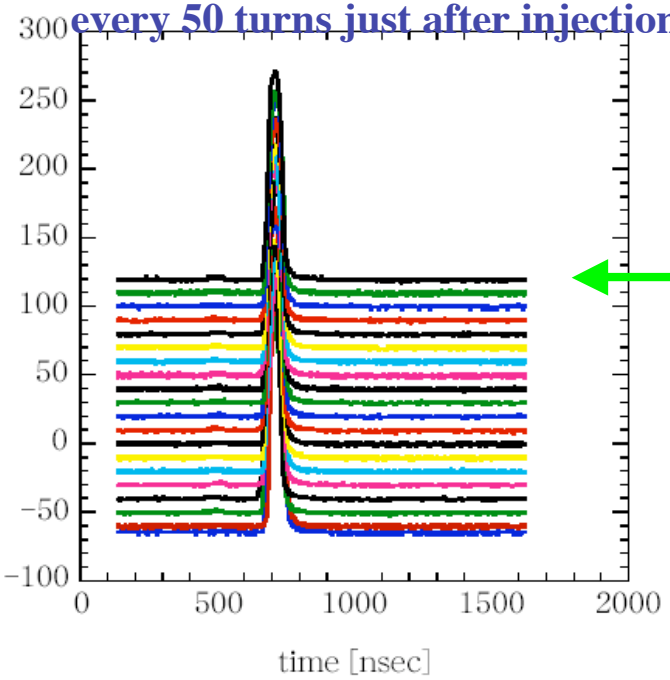


**RF On**

**every 50 turns just after injection**

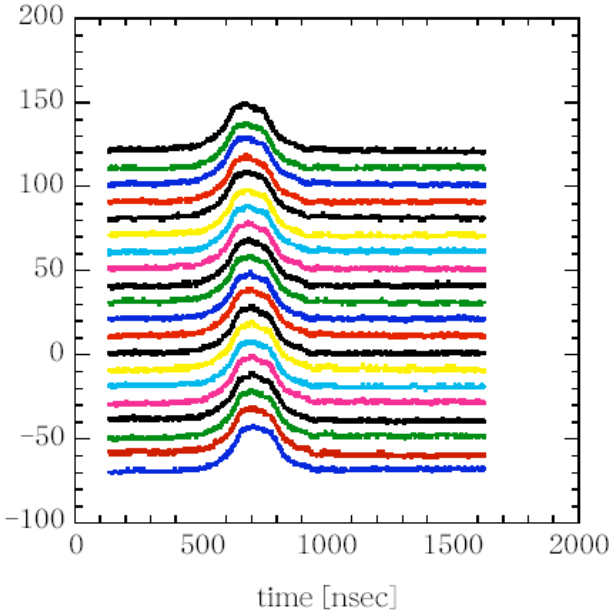



**Mountain View**

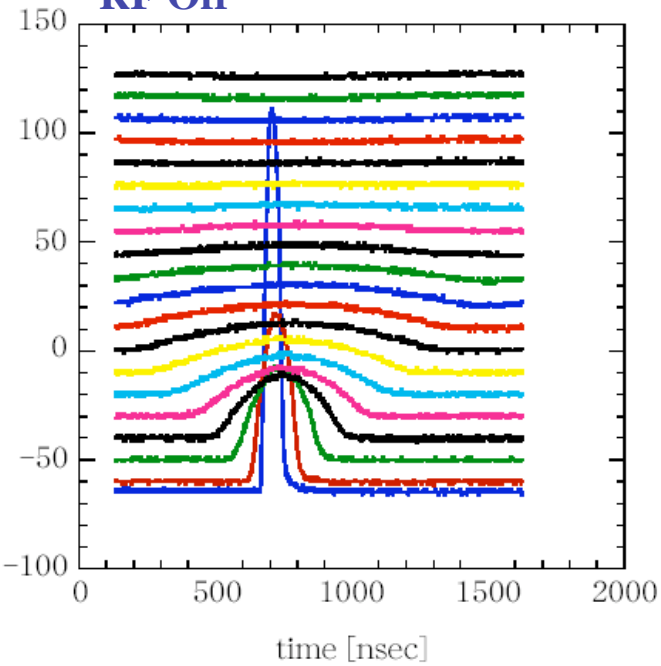
**RF bucket Trapping**

**150msec after injection**

**every 1 turn**



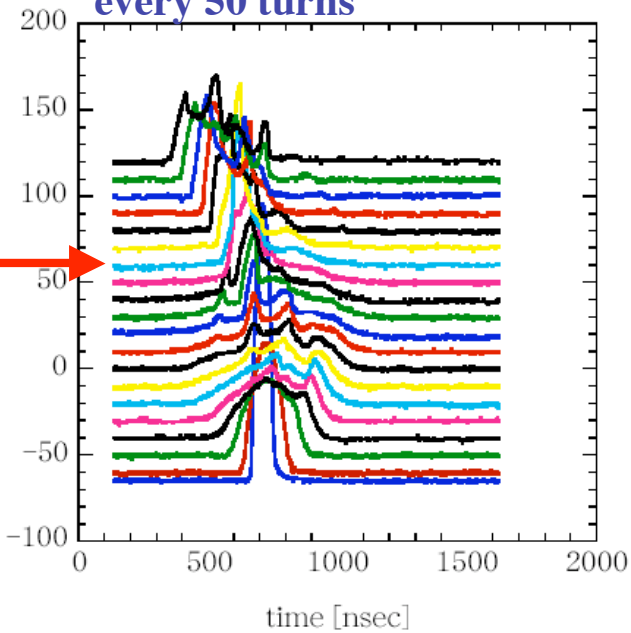

**RF Off**



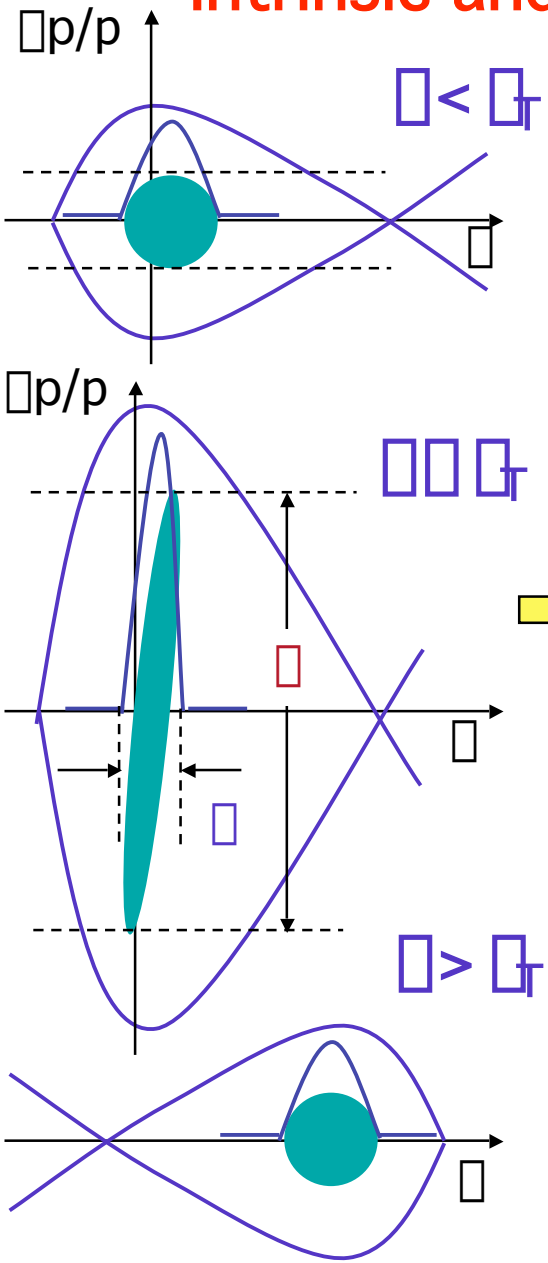

**Notch Potential Trapping**

**just after injection**

**every 50 turns**



# Intrinsic and Fatal Issues In Transition Crossing



- **Increasing of space-charge effects**
- **Increasing of e-cloud（RHIC）**
- **Coherent instability**
  **Microwave instability(KEK-PS)**

**Bunch shortening**

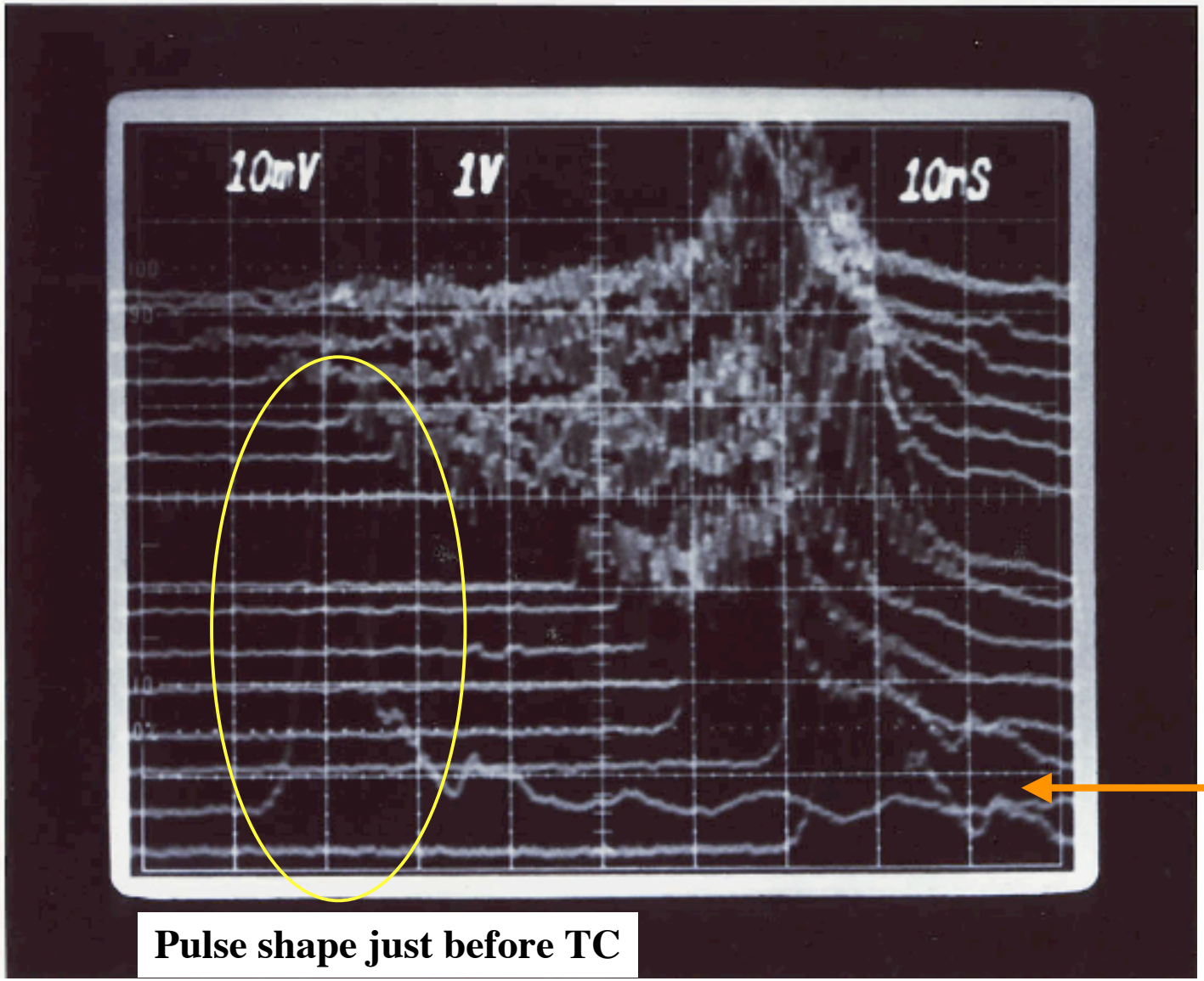
**Momentum spread expansion**

**Emittance blow-up**
**Beam-loss**

- **Reduction of momentum-aperture margin**
- **Mismatching in the phase-space due to Johnsen Effects (FNAL-MR, RHIC)**

# Microwave Instability observed in the KEK PS

N = 6×10"/ bunch



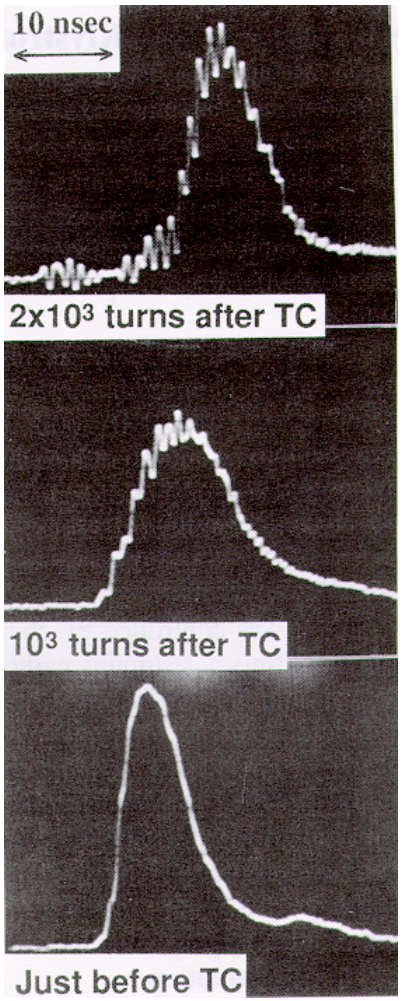

Pulse shape just before TC

every 5/2
(~800

Phase Jump

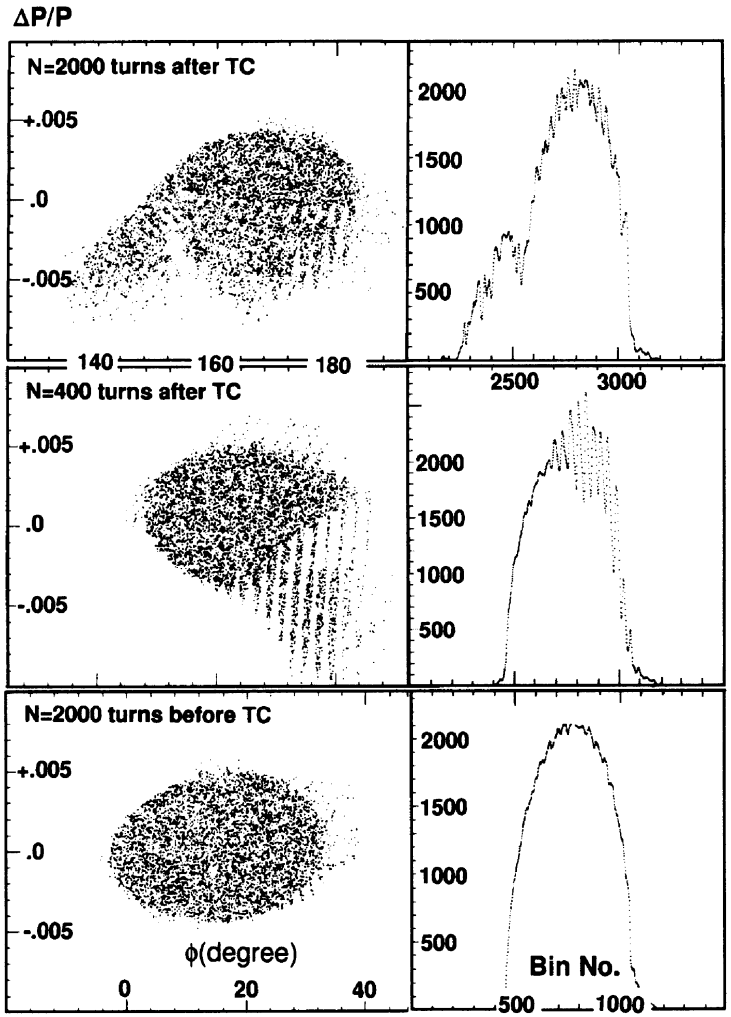
# Microwave Instability: comparison with simulations

**Line density (measurement)**

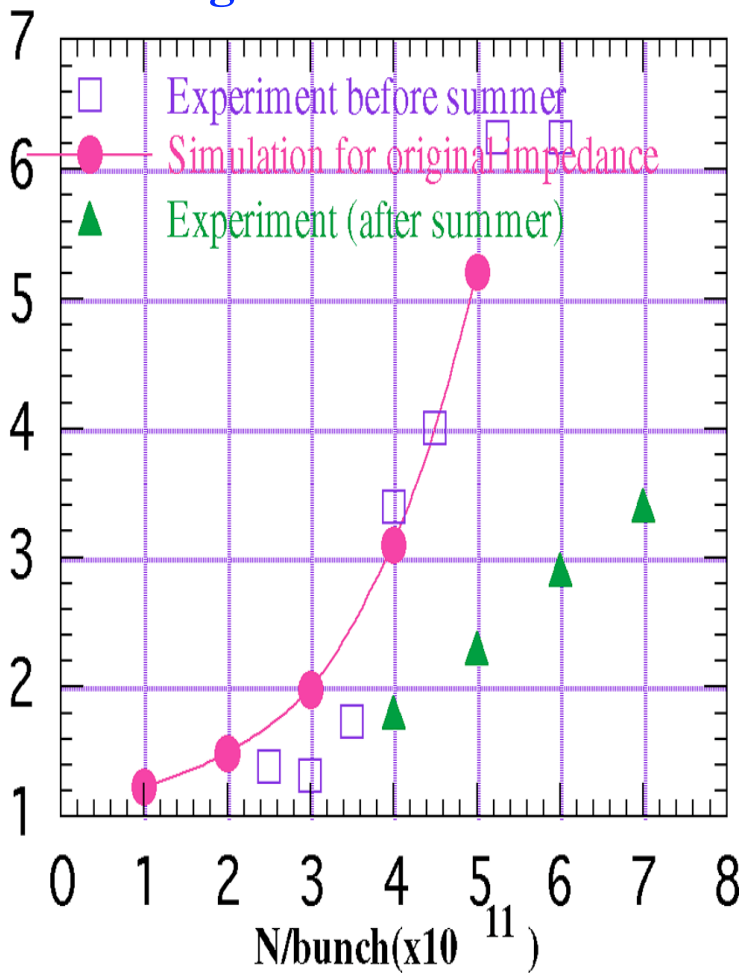



**Phase space dist.**

**Line density (simulation)**




**Longitudinal Emittance**



# Focusing-free Transition Crossing (FFTC)

- Focusing voltage is turned off around Transition energy.
- Acceleration voltage is provided as a flat voltage.

**In RF Synchrotron (in hybrid scheme):**

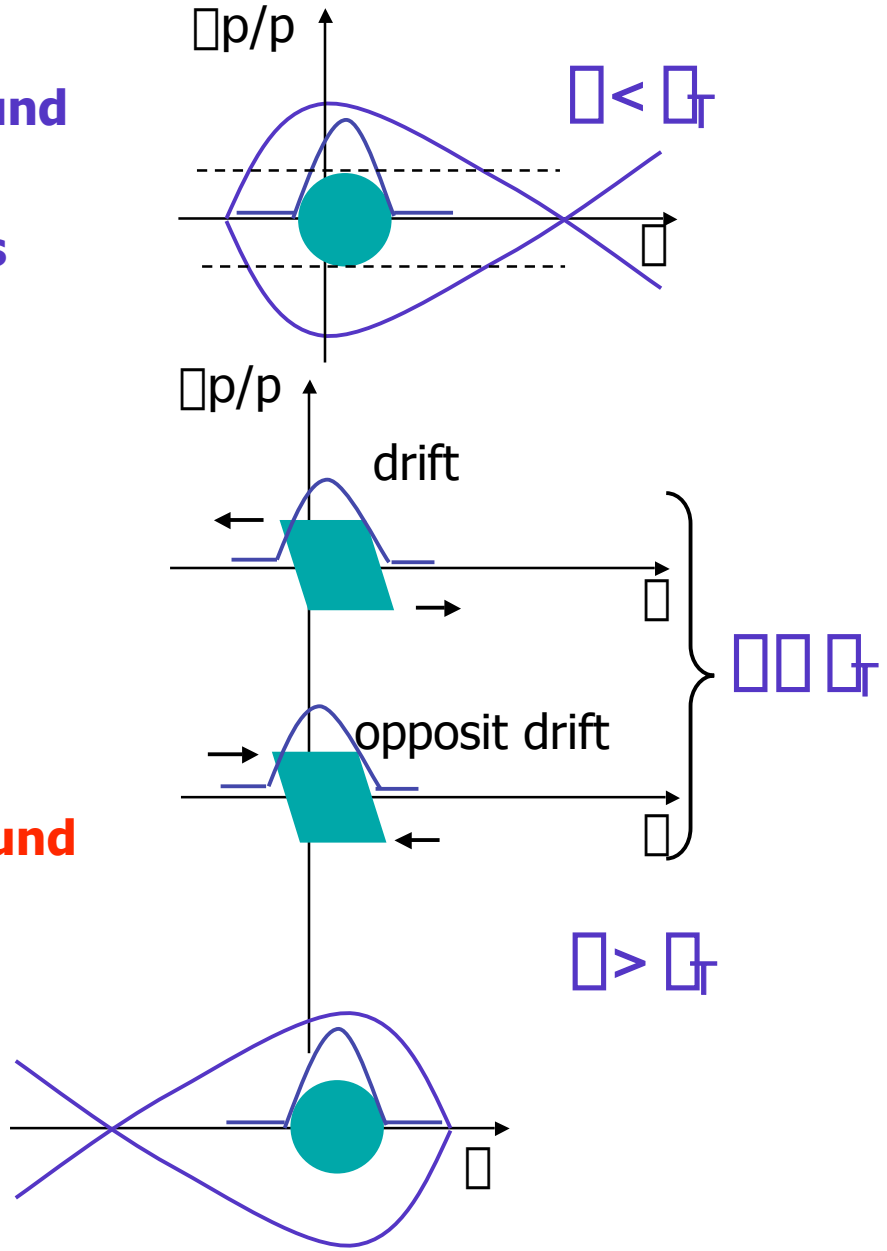
- RF voltage is turned off around Transition energy.
- Induction voltage is triggered。

**In Induction Synchrotron:**

- Barrier voltage only is turned off around Transition energy.

$$E_{n+1} = E_n + eV_{acc}$$

$$\phi_{n+1} = \left[ \phi_{n+1} + 2\pi h \left( \frac{1}{\gamma_T^2} - \frac{1}{\gamma_s^2} \right) \frac{\Delta p}{p} \right]_{\mathrm{mod}\ 2\pi}$$



## A possible scheme of focusing-free TC POP experiments in RHIC

- with minor changes of RHIC, such as a lower ramping pattern of B
- introducing induction devices which are available from KEK

### Parameters for the induction cavity

2006:

| | |
|---|---|
| output voltage | 2 kV/cell |
| pulse length | 100-400 nsec (variable) |
| rep-rate | - 1 MHz |
| cell length | 25 cm |

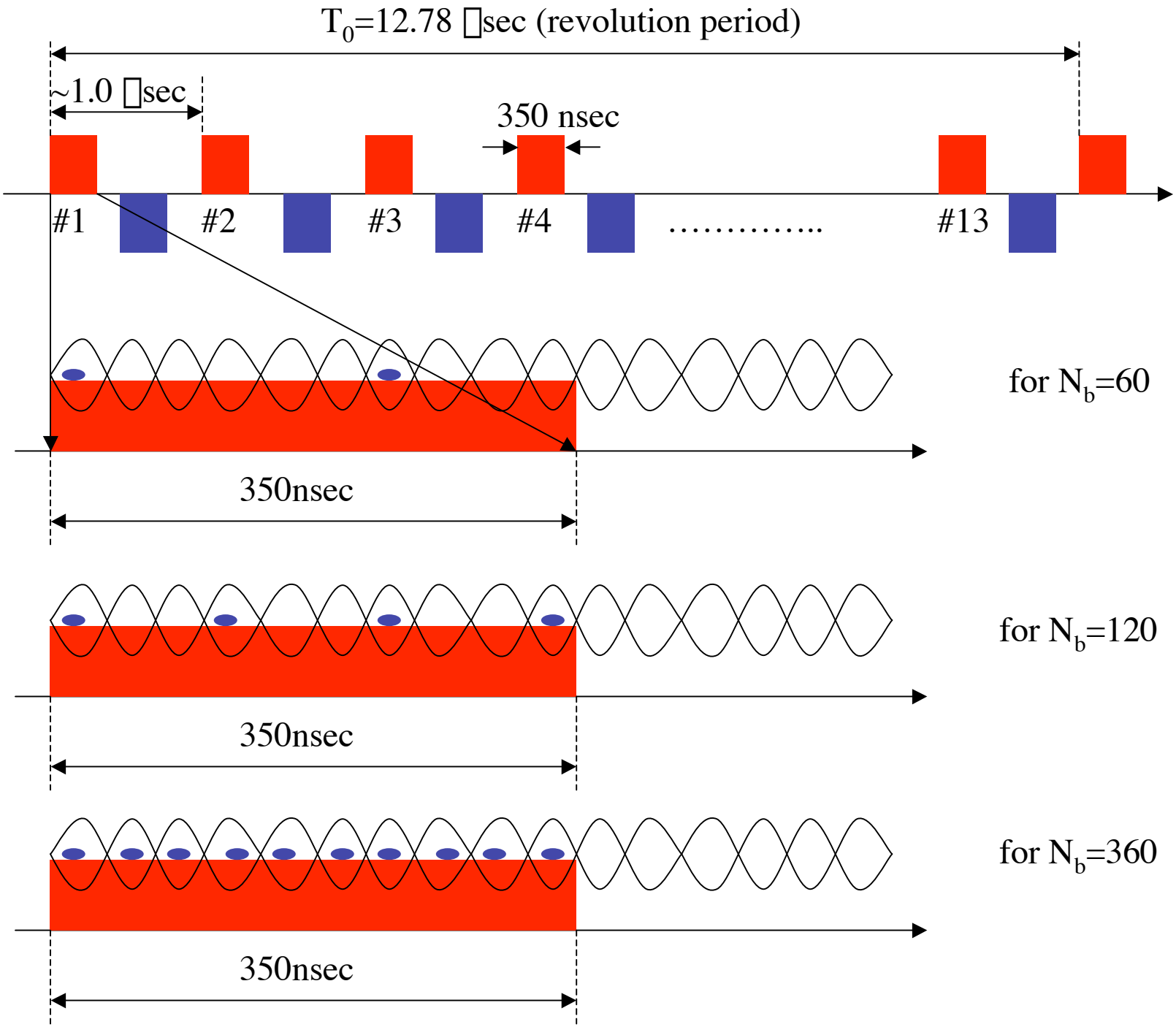
24 kV induction acceleration system  12 x 0.25 m=3 m long

2007-8:

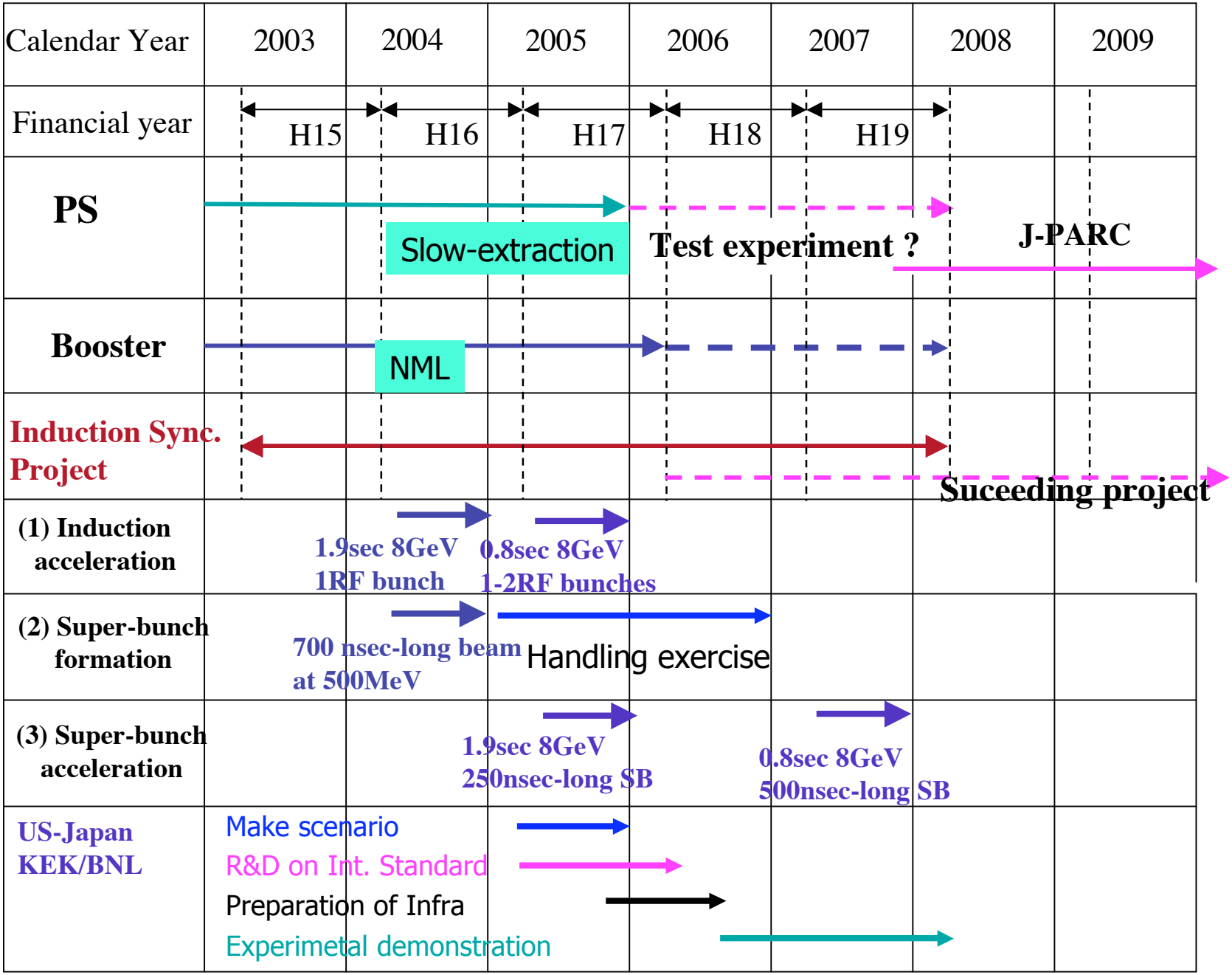
48 kV induction acceleration system  24 x 0.25 m=6 m long

### Cost estimation

0.15 M$/2kV  ->  1.8 M$


T0=12.78 □sec (revolution period)
~1.0 □sec
350 nsec
#1
#2
#3
#4
……..
#13
for Nb=60
350nsec
for Nb=120
350nsec
for Nb=360
350nsec

# KEK-PS operation schedule & Road Map



# Summary

- A reliable full module for the induction accelerating system consisting of 50kW DC P.S., Pulse Modulator, Transmission Cable, Matching Resistance, Induction Cell, which is capable of operating at 1 MHz, has been confirmed to run over 24 hours without any troubles.
- The *induction acceleration* of protons($6\times10^{11}$ppb) in a circular accelerator ring has been observed, where a single RF bunch was accelerated from 500MeV to 8GeV (flat-top) with an energy gain of 4.8 kV/turn.
- A *600nsec-long proton bunch* trapped in a shallow notch potential, which is generated with induction step-voltages, has been demonstrated.
- These results are crucial milestones to realize *Induction Synchrotrons* and *Super-bunch Hadron Colliders* (K.Takayama et al., *PRL* 88, 1448(2002)).
  They will be published in *PRL* (April issue) and *PRE*(submitted).
- The acceleration in circular rings has entered into a new era with induction devices driven by a switching driver.

# Announcement

# RPIA2006

## International Workshop on
## Recent Progress in Induction Accelerators
## in Tsukuba or Tokyo
## January 2006

**We will discuss**

- **Induction devices for LINAC and Circular Ring**
  **(Cavity, Modulator, Switching elements, System architecture)**
- **Hybrid system combining RF and Induction acceleration**
- **Beam dynamics in extremely high intensity accelerators**
- **Super-bunch beam dynamics, barrier-bucket beam dynamics**
- **Applications**

**(Chopper, High-rep rate Kicker, Induction Synchrotron, Super-bunch FFAG, Super-bunch Hadoron Collider, Heavy Ion Fusion Driver, Novel Ion Accelerator)**

**Contributions from Proton driver, Neutrino Factory, Hadron Collider, Inertial Fusion, Pulsed-power technology, Linear Collider Societies quite welcome**